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MODELLING OF AN EXPANDABLE, RECONFIGURABLE, RENEWABLE DC MICROGRID FOR OFF-GRID COMMUNITIES

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Abstract

This paper proposes a DC microgrid system based on multiple locally available renewable energy sources in an off-grid rural community, based on a field study carried out in a rural, off-grid village in Nepal. The site has been assessed as suitable for solar and wind power. Using estimated solar data for the site's location, wind data measured locally, household and population data and typical measured domestic demand profiles, a DC microgrid system model has been constructed. Power flow is controlled using modified DC droop control on each individual energy source to enable optimal power sharing with minimum power dissipation across distribution lines.

Keywords: DC microgrid, DC droop control, Solar, Wind

1 INTRODUCTION

Of the 1.2 billion people who do not have access to electricity, nearly 85% are in rural areas [1], and most of these will require off-grid solutions to achieve the U.N.'s goal of universal energy access by 2030 [2]. For these solutions, renewable generation technologies are often the most appropriate, as they are sustainable and allow local power generation without any requirement for external energy supply. Off-grid renewable solutions are normally on an individual household scale, such as the Solar-Home System (SHS), or community scale solutions, where a single resource powers multiple households such as a micro-hydro scheme. Microgrids have emerged as an opportunity to connect multiple sources and loads that are in close geographic location, and can be either grid-connected or islanded.

Both AC- and DC-based microgrids have been investigated [3], with benefits and drawbacks to each type of system. DC microgrids have advantages of simpler control with no requirement for synchronisation, and are able to integrate renewable sources such as photovoltaics and battery storage easier than AC networks. Primary control for DC microgrids can be based on droop mechanisms, where the output voltage of a source reduces as the power demand

increases, mimicking grid attributes [3]. This can be achieved artificially through power electronic interfaces, with further levels of control added as required [4].

This paper proposes and simulates a modular DC microgrid system in which the sources interfaced with the DC grid via droop control. Section 2 describes the overall system layout and design; Section 3 details the case study site; Section 4 presents the results from the simulation of the case study site.

2 DC MICROGRID SYSTEM OVERVIEW

The DC microgrid links together sources and loads in a common location; the sources and loads can be scattered across the implementation area, as shown diagrammatically in Figure 1.

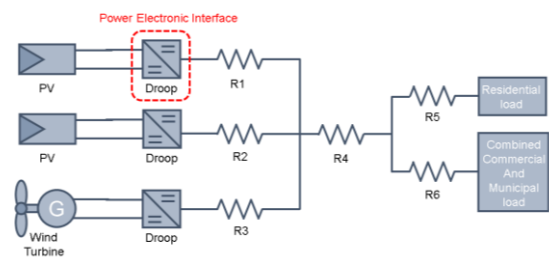


Figure 1. Diagram of off-grid distributed DC multi-source, multi-load system.

Each source is connected onto the grid through a modular power electronic interface. The power electronic interface includes a grid interfacing converter which changes the voltage to the grid level, and uses droop control to manage the power flow onto the grid.

Droop control is used to control the power flow of the system without the need for communication between sources. For DC systems, the converter measures its output power or current and adjusts the output voltage. This is typically implemented as a linear relationship; thus, for sources that are separated by transmission and distribution lines, there is a trade-off between voltage regulation and power sharing. However, a novel system has been proposed in [7], which uses a non-linear droop curve, shown in Figure 3. This allows for good power sharing at low and high power, whilst minimising change in grid voltage. As with a linear droop scheme, this system can be scaled dependent on ratio of available power to maximum power [8]. This scheme is applied in the DC microgrid model, with the Matlab code written for this work is shown in Figure 2.

```
function [Rd,Vref,newVnom,alpha,deltaV] =
droop (Rdmax,Imax,Vnom,Vmin,I)
%INPUTS:
%Rdmax = modulus of maximum droop gain
%Imax = maximum current available
%Vnom = nominal voltage
%Vmin = min acceptable voltage
%I= source's output current
%alpha is the arc co-efficient
alpha=(Rdmax*Imax)/(Vnom-Vmin);
% Rd = a range of droop gain (always
negative)
Rd=((I^(alpha - 1)*alpha*(Vmin -
Vnom))/Imax^alpha);
%deltaV is the amount by which Vnom must
be shifted up
deltaV=((alpha-1)*(Vnom-
Vmin)*I^alpha)/(Imax^alpha);
newVnom=Vnom+deltaV;
%OUTPUTS:
Vref=newVnom+Rd*I;
```

Figure 2. Modified DC droop control implemented in embedded Matlab code

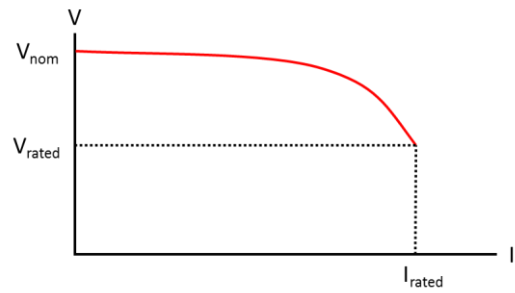


Figure 3. Droop control Curve

The grid transmission and distribution system is constructed from wires, which can be assumed to be simple resistances for low voltage cables. The loads for the DC microgrid are assumed to connect directly onto the grid.

3 CASE STUDY SITE: MITYAL, NEPAL

The DC microgrid system described in Section 2 is simulated through a case study example, informed by data from a field study, carried out in Mityal VDC, Palpa, Nepal [9]. The most pertinent local site details are set out in Table. 1. The survey assessed both existing and potential availability of off-grid supply sources, and provided background information to assist in assessing the future demand and installation requirements for a microgrid in this area.

3.1 Modelled DC microgrid system

A DC microgrid system based on the site study in Mityal, has been created in Simulink. This model considers the change in loads and sources on an hour by hour basis, using the available load, wind and solar data. No energy storage has been included in this model, but it will be used as a basis in future work for specifying the minimum amount of system storage required together with HOMER software [10]

Table. 1 Summary of Information from Field Study Site in Nepal

Site name	Mityal VDC, Palpa, Nepal
Co-ordinates	27°46' N 83°55'E
Elevation above sea level	957 metres
No. of households (population)	54 (300)
Available renewable energy sources	Solar, wind
Currently installed renewable power	Average SHS 39 W (min 10 W, max. 180W) 2.4 kW solar system on school
Currently installed non-renewable power	Commercial - Rice mill diesel engine 7.4 kW Domestic – wood, liquid petroleum gas (LPG)
Domestic power demand (daily average)	6.61 kW average (summer), 3.91 kW (winter)
Domestic energy demand per day	58.53kWh (summer), 30.05kWh (winter)
Current total commercial energy demand per day	86.6kWh (rice mill, water pump, office equipment)
Current municipal services demand	2kW for health posts, police station
New renewable installations recommended by PEEDA to meet current demand	Three 5kW wind turbines (total 15 kW), 16 solar panels of 310 W each (aggregate of 5 kW solar)

In order to maintain the Simulink model's relative simplicity a version scaled to 1/10th of the full hybrid wind-solar installation recommended by the field report [9] with typical site loads is created. The model's main features are set out in Table 2. and employ 1.5 kW wind turbine and 500 W solar based on models previously compiled by the authors [6], [11]. The main features of the DC multi-source multi-load system are listed in Table 2.

Table 2. Summary of Power Sources, Loads and DC Network Simulation Parameters

Simulated Network Characteristics (10:1)	Details
Wind turbine	1.5 kW rated
25 x SLP020 20 W solar panels	aggregate solar power: 500 W
Transmission/distribution resistances (Figure 1)	R1, R2 = 4.3 mΩ, R3 = 8.5 mΩ, R4 = 420 mΩ R5, R6 = 150 mΩ
DC distributed network	400 V rated +/- 5% at source
System voltage drop	≤ 10%
Domestic load	5.85 kWh in 1 day
Commercial load	8.66. kWh in 1 day
Municipal load	1.20 kWh in 1 day

3.2 Modelling Demand over 24 hours

The field study has provided estimates of the composite domestic, commercial and municipal energy demand per day (Table. 1). However, the

instantaneous power demand will follow an irregular pattern over the course of a day.

Domestic Instantaneous Power Demand

Figure 4 shows the typical rural domestic consumption pattern over a 24-hour period in October, based on measured data from Bhanbhane, Gulmi, Nepal in 2012 [12]. It exhibits typical Nepalese rural domestic consumption patterns over a day, and therefore has been adapted for use in modelling the rural load considered in this work. The measured power over the course of a day on one household gave rise to a total energy consumption of 0.39 kWh; this has been normalised to 1 kWh energy consumption over the course of 24 hours as shown in Figure 4

The scaled profile varying domestic demand over the course of a day, shown in Figure 4 was used as an input to the load model in Simulink. Based on a given power consumption profile and measured grid voltage, a signal could be generated to control a controlled current source emulating a load, as shown in Figure 5.

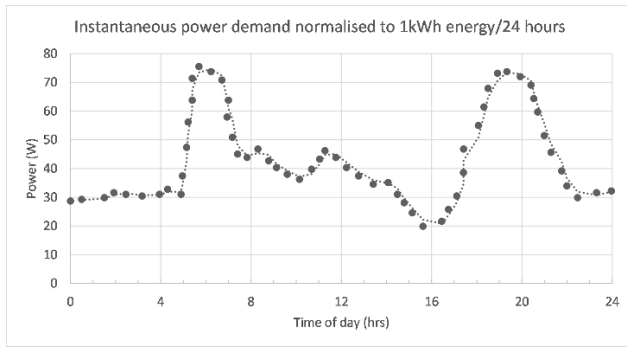


Figure 4. Measured rural domestic power consumption pattern in Nepal over 24-hour period (normalised to 1 kWh)

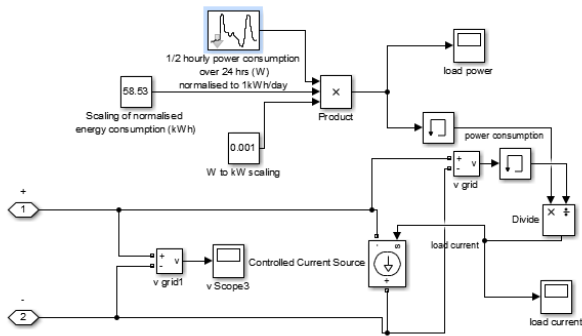


Figure 5. Simulating 24-hour domestic load with scaled variable power consumption

Commercial and Municipal Power

The commercial and municipal power consumption is more predictable than domestic over the course of 24 hours and is shown in Figure 6. The commercial load is comprised of a water pump, rice mill, and office requirements (photocopy machine and printer). The municipal load comprises office lighting and equipment requirements for a health post, police station, co-operative, VDC office and forestry office.

The separate and combined commercial and municipal power load over the course of 24 hours is also shown in Figure 6. The composite load is modelled in Simulink as a second load using the same technique as the domestic load.

3.3 Modelling Solar Power

The solar panel models used are taken from [11], their details are set out in Table 2.

Local Solar Data

Using site GPS co-ordinates, daily averaged solar data from NASA [13] is used. The site provides an average insolation energy of 5.22 kWh/m²/day

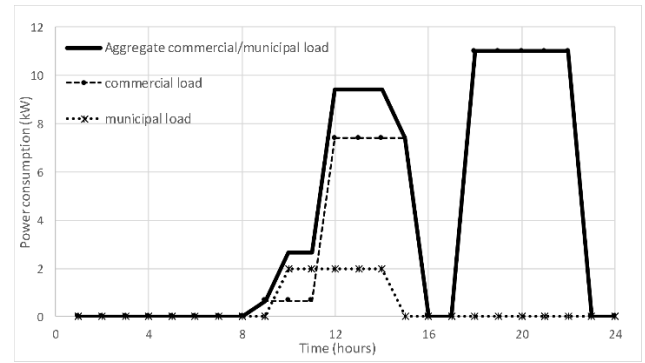


Figure 6. Commercial and municipal power consumption requirements in Mityal over 24 hours

over the course of a year, increasing in June to 5.8 kWh/m²/day. Assuming no cloud cover or shading, the insolation power varies diurnally [14], shown in Figure 7, reaching a maximum of 1,012 W/m². This is then used as an input to the solar panel models.

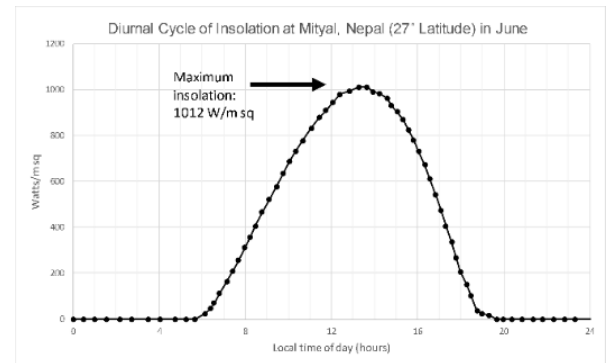


Figure 7. Diurnal cycle of insolation at Mityal (27 ° latitude) in June

Local Temperature Data

Photovoltaic panel performance is temperature dependent, and is an input for the solar panel model. There is no locally recorded temperature information, so an average temperature based on the site location [15] has been used, which is 28.1 °C in June.

3.4 Modelling wind power

Wind data was recorded at the site every 10 minutes, and averaged every 2 hours, over a period of 9 months at 20, 30 and 40m by the Alternative Energy Promotion Centre, Nepal [9]. This averaged wind speed data is combined with gust modelling, using a small Gaussian distributed random signal with a mean of 0 m/s and a variance of 3 m/s, to determine the wind speed. The wind turbine model used in the simulation is a 1.5 kW turbine model [6], with parameters in Table 2.

3.5 Line Resistances

Standard 100 mm² Aluminium Conductor Steel Reinforced (ACSR) lines have been selected for the transmission and distribution lines [9], which will have a resistance of 0.30 Ω /km [16]. The distance between the wind turbine and solar panel and the power house, where the solar and wind resource connection points are, is assumed to be 28.3 m and 14.2 m respectively. The approximate distance of the transmission line running between the power house site and the village captured during the field visit and was measured to be 1.4 km. Within Mityal village the total distribution wire length was measured to be 1 km. For simplicity, the composite village demand has been modelled as two separate loads, each with cabling to them of 0.5 km. The transmission and distribution distances are illustrated as resistances in Figure 1, and their details are in Table 2.

3.6 Droop Control Parameters

The droop curve shown in Figure 3 are used in this simulation, with $V_{nom} = 420$ V and $V_{rated} = 400$ V. The maximum current, I_{rated} is dependent on the power available to the source, and is scaled, as described in Section 2 and [8].

Droop Curve Scaling

The maximum output power from solar panels is approximately proportional to the product of their power rating and insolation, ignoring temperature effects and will therefore vary. Accordingly, the maximum power available from the solar panel, based on the rated panel power at standard conditions and the insolation, is fed forward into the droop controller, as in Figure 8. This sets the value of the maximum current I_{rated} for droop control at minimum voltage V_{rated} , in Figure 3.

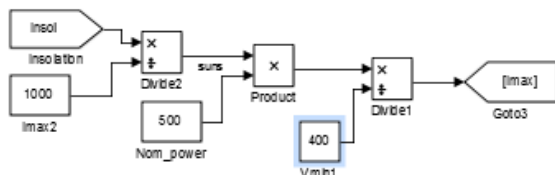


Figure 8. Feed forward of solar power (based on insolation) into droop controller

For the wind turbine, the output power is directly proportional to the cube of the wind speed. As the rated power of the wind turbine at rated speed of 10 m/s is 1.5 kW, the droop control permits the output voltage to range from its nominal 420 V down to a minimum of 400 V at full output power. Therefore, I_{rated} for the wind turbine droop control is 3.947 A at 10 m/s wind speed.

4 CASE STUDY SIMULATION RESULTS

The system model is shown below over a period of 10 hours 11am – 9pm. Figure 9 (top) shows the current being drawn from the solar source; the square shape is attributable to the combined commercial/municipal load profile. Figure 9 (middle) illustrates the decrease in droop control voltage reference with insolation (bottom).

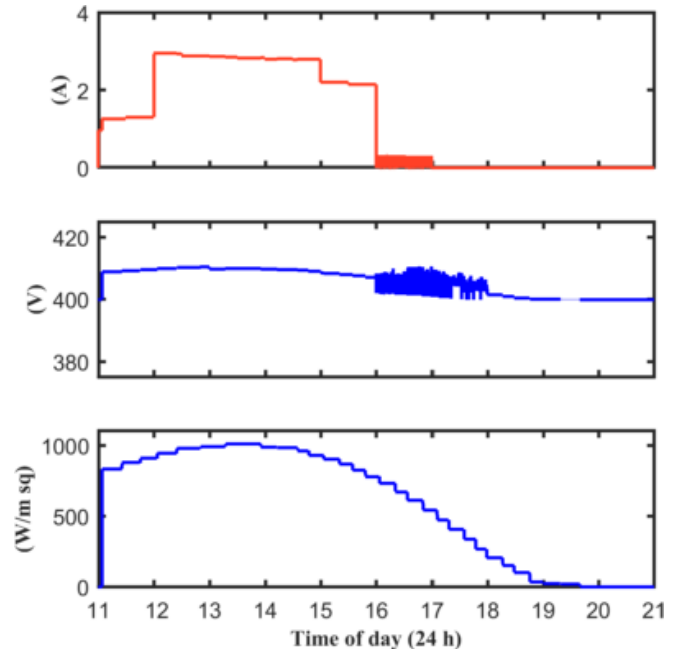


Figure 9. Solar output: current (top), droop control reference (middle), insolation (bottom)

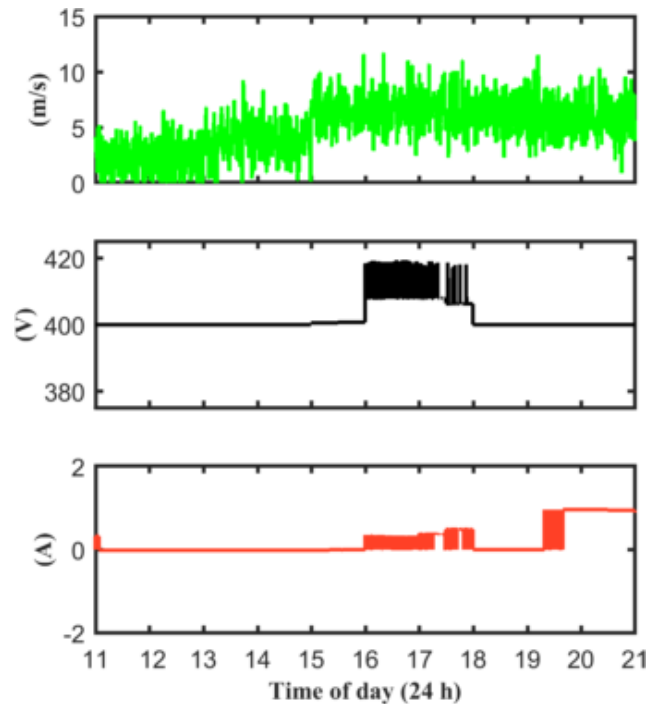


Figure 10. Wind turbine: wind speed (top), droop control reference (middle), current (bottom)

Figure 10 sets out data for the wind turbine. Between 1100-1500 hours, wind speed (top) is lower, therefore the droop reference voltage (middle) is at its minimum of 400V. During 1600-1800 hrs most of the load current is being drawn from solar, therefore the droop reference voltage Figure 10 (middle) is higher.

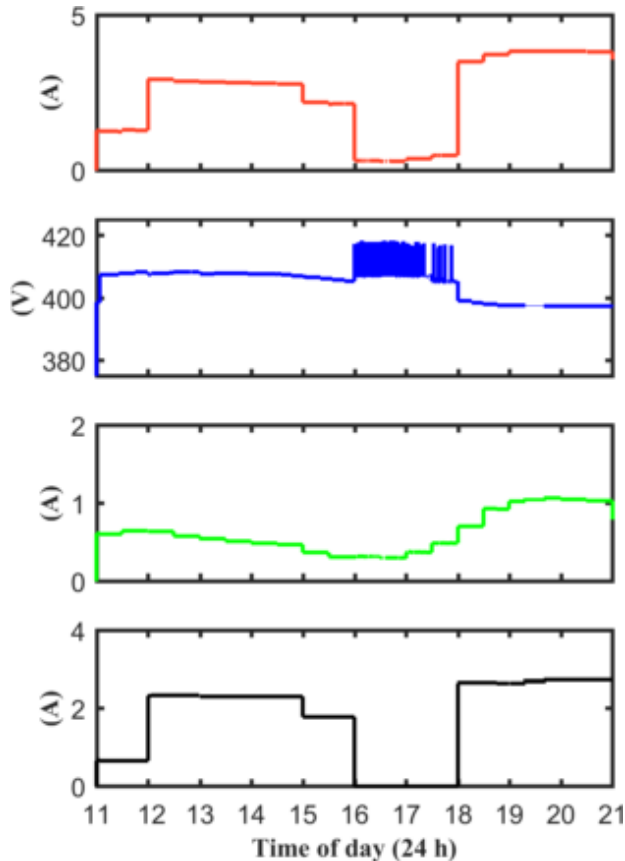


Figure 11. Grid and Loads: grid current (top), grid voltage (middle), domestic load (green), commercial load (bottom)

Figure 11 shows the grid current and voltage, and load currents during 1100-2100 timeframe. It will be noted from this that there is a slump in grid voltage at high loads, particularly 1800-2100 hrs as there is no storage to provide additional power during periods of demand-supply mismatch.

5 CONCLUSIONS

This paper has presented a DC microgrid system, interfacing renewable sources using a power electronic interface with droop functions. A case study site in Mityal, Nepal is simulated to demonstrate the performance of the system to variable generation and loads. The simulation has illustrated power sharing between wind and solar sources through droop control and in response to changing parameters over the course of a day such as loads and insolation. Future work in this area

will focus on specifying the amount of storage required for this system.

ACKNOWLEDGEMENTS

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